Chapter 2. Sensitivities of Terrestrial and Aquatic Ecosystems to Air Pollutants

Air quality impacts in National Parks and Monuments include the potential effects of pollutants on terrestrial and aquatic ecosystems. In general, impacts on terrestrial ecosystems are considered as impacts on plants because animals are generally considered to be less sensitive to most pollutants. Exceptions to this generalization may include sensitivity of wildlife species to ozone, but we found no information that would provide a basis for evaluating potential wildlife impacts (such as ozone damage) on the Colorado Plateau. Therefore, our discussion of sensitivity of ecosystems focuses on plants for terrestrial ecosystems, and on chemistry, plants and animals of aquatic ecosystems.

Ozone

Ozone (O_3) is an important component of the upper atmosphere, where it forms naturally when molecular oxygen (O_2) absorbs ultraviolet light. This atmospheric layer of ozone in the stratosphere is crucial for absorbing potentially damaging ultraviolet radiation. In the troposphere near the ground, ozone can be produced through a variety of reactions among air pollutants, and high concentrations of ozone may harm plants and animals. Ozone forms in the lower atmosphere primarily when light splits nitrogen dioxide (NO_2) into nitric oxide (NO) and a single oxygen atom (O), which then combines with molecular oxygen (O_2) to form ozone. The presence of hydrocarbons (especially aldehydes and ketones, produced by both vegetation and combustion of fossil fuels) can accelerate ozone formation. When these hydrocarbons absorb light, they can produce free radicals (highly reactive compounds with unpaired electrons, such as peroxyl radicals) which accelerate the splitting of nitrogen dioxide. Ozone concentrations tend to be highest in the afternoon as a result of production of nitrogen dioxide and hydrocarbons earlier in the day (Wellburn 1988, Böhm 1992).

Ozone damages plants (and animals) by oxidizing important biochemicals. Ozone uptake in plants occurs primarily through open stomates, so ozone exposure is relatively low during the night or during periods of moisture stress when stomates are closed. Once inside the mesophyll of leaves, cell walls offer little resistance to diffusion of ozone. A wide variety of reactions occur once ozone enters cells. Proteins and fatty acids are attacked, leading to increased membrane permeability (and "leaking"). When ozone damage is light, membranes can be repaired and leakage of sugars, potassium and other compounds declines (Wellburn 1988). Higher levels of exposure lead to irreparable damage to a variety of cell membranes, organelles, and functions.

Visible injury to plant leaves typically include small flecks of yellow (chlorotic flecking) or purple and black that may develop into larger regions (mottling). In western conifers, needle tips tend to show chlorotic mottling first, with symptoms spreading toward the base of the needles; needles with more than 50% chlorotic mottling typically die, leading to sparsely foliated branches (Stolte et al. 1992). Species vary substantially in sensitivity to ozone, and within species some genotypes can be more susceptible than others.

The overall syndrome of ozone impacts involves many steps in plant biochemistry and ecology. Ozone may reduce the leaf area and photosynthesis of plants, lowering growth and also lowering resistance to pests and pathogens. Ozone stress typically does not kill plants, but lower carbohydrate supplies may reduce resistance to a point where pests, such as bark beetles on Jeffrey pine in southern California, substantially increase mortality rates (Miller 1992). The actual mechanisms of reduced resistance to insects and pathogens probably relate to altered carbon status of the trees, including balances between secondary compounds and other biochemicals.

Animals are also susceptible to high ozone concentrations; ozone irritates eyes and bronchial passages by disrupting cell membranes.

Ozone concentrations are typically highest near urban centers, where the precursor chemicals are produced in abundance. The half-life of ozone in the column of air in the lower atmosphere is about 2-4 weeks [Intergovernmental Panel on Climate Change (IPCC) 1994]; close to the ground, ozone is consumed even more quickly by reaction with vegetation. This half-life is short enough to insure that the highest ozone concentrations will be near the sources of nitrogen dioxide and hydrocarbon pollution, but long enough to allow elevated concentrations to move with air masses to more remote locations.

A variety of approaches have been used to characterize sensitivity of plants to ozone, including average hourly exposure, exposure to peak concentrations, and weighted average exposures where high concentration periods are weighted more heavily than low periods (Lefohn and Foley 1993).   Fox et al. (1989) suggested that ozone concentrations below 35 ppb for a growing season average, or 75 ppb peak, would represent no threat to vegetation in Class I areas. The range of possible impacts for the most sensitive species was thought to begin somewhere between 35 and 55 ppb for growing season averages, with peaks up to 110 ppb. Beyond these levels, sensitive plants should develop signs of injury.

Heck and Cowling (in press) summarized consensus from a workshop that was held to define critical levels of ozone for impacts on plants.   For natural ecosystems, this group concluded that foliar injury may be the best indicator of ozone damage; additional information would focus on levels

of ozone that would result in reduced tree growth in natural forests or plantations. The workshop participants concluded that the best measure of ozone exposure would combine both concentration and duration of exposure; the "sum60" value multiplies the ozone concentration in excess of 60 ppb by the number of hours, for a period of 12 hrs/day summed over 90 days of the growing season. This index may be viewed as a "threshold weighting" index rather than an index that would weight periods of higher concentrations more heavily (Musselman et al. 1995). Foliar injury should be prevented if the "sum60" exposure remained below 8000 to 12000 ppb-hrs., and growth impacts should be prevented if exposures remained below 10000 to 16000 ppb-hrs. Exposures above this level may represent a potential threat to sensitive species, although less-sensitive species may be susceptible only to much higher exposures.

As mentioned in Chapter 1, the EPA is proposing a revised secondary standard for ozone concentrations to protect plants. The criteria document (EPA 1996) recommends a much higher threshold for the secondary standard than Heck and Cowling (in press); the secondary standard would be set at 25000 to 38000 ppb-hrs (for 12 hrs/day and a 90-day season).

The cumulative ozone exposures on the Colorado Plateau (Chapter 1) commonly fall within the range suggested by Heck and Cowling (in press) as leading to foliar injury on sensitive species, and some years at some locations fall into the range where they suggest sensitive species may show growth reductions. In contrast, only one year (1991) at one area (Bandelier) exceeded the secondary standard of 25000 ppb-hrs suggested by the EPA staff paper (EPA 1996).

The applicability of the current and proposed ozone standards to conditions on the Colorado Plateau may be problematic. The semi-arid nature of the landscape leads to prolonged periods where many plants will have closed stomata, reducing the uptake of ozone. We expect that actually doses of ozone experienced by plants on the Colorado Plateau will generally be lower than those experienced by plants in wetter regions at equivalent exposures to atmospheric concentrations.

The sensitivity of plants can be examined with controlled fumigation studies, with the exposure characterized by the peak concentration (such as the 120 ppb standard) or by cumulative, chronic exposure (such as the Sum60 index or similar threshold approaches). These controlled studies need to be supplemented by field studies that search for characteristic signs of chlorotic flecking (stippling) and mottling from ozone exposure.

No reports of visible injury or growth reduction from ozone (or other pollutants) have been registered for the Colorado Plateau. This absence of evidence could result from an absence of impact, or from the paucity of direct examinations.

In the absence of evidence of injury, inferences about the potential sensitivity of species on the Colorado Plateau to ozone can be based on controlled exposure studies. Unfortunately, only a few of the major species from the Colorado Plateau have been tested in controlled experiments for sensitivity to ozone. We surveyed the literature for available information on controlled exposure experiments for species that occur in one or more of the NPS Class I areas of the Colorado Plateau. Tables 2-1 (trees and shrubs) and 2-2 (forbs and grasses) summarize this information, rating species as sensitive or not-sensitive for 3 levels of peak ozone exposure. Species were rated as "sensitive" if they showed any response to a given level of ozone exposure, including visible foliar injury or growth rate. The occurrence of species in each park or monument was based on NPFlora listing. Any species that did not show sensitivities in studies at 120 ppb or lower are probably relatively resistant to ozone effects at ambient concentrations on the Colorado Plateau. Species that demonstrated some sensitivity at 120 ppb or lower are discussed in more detail below.

Controlled exposure experiments have a variety of challenges for determining ozone sensitivity of plants (Pye 1988), including:

- developing a proper "control" treatment; use of ambient air may include a significant exposure to ozone, but use of charcoal-filtered air introduces other artifacts;
- developing a realistic exposure profile, including peak concentrations, diurnal and seasonal variation, length of exposure period;
- environmental conditions (particularly supply of water and nutrients);
- size and age of the plants (particularly important for trees); and
- selection of response variables to be measured, such as gas exchange or biomass.

Based on the available literature, only a few tree species are potentially sensitive to peak ozone concentrations of < 120 ppb (Table 2-1). The major tree species on the Colorado Plateau that appears sensitive to ozone is aspen (*Populus tremuloides*).

Table 2-1. Reported sensitivity of tree and shrub species to ozone. N = not sensitive, X = sensitive by some measure, and blanks indicate no reported information. Species is absent (0) or present (1) in the park or monument.

Species	Authority	Family	Common name	Ozone (ppb) range N=not sensitive X=sensitive 0-120	121-200	>200	ARCH	BAND	BLCA	BRCA	CANY	CARE	GRCA	GRSA	MEVE	PEFO	ZION	References
Abies concolor	(Gord. & Glend.) Lindl.	Pinaceae	white fir	N	N	N/X	0	1	0	1	1	0	1	1	0	0	1	Davis & Wilhour 1976; Davis & Wood 1972; Miller & Millecan 1971; Miller et al. 1983; Treshow & Stewart 1973; Bytnerowicz & Grulke 1992
Acacia greggii	Gray	Fabaceae	catclaw acacia	N	N		0	0	0	0	0	0	1	0	0	0	0	Temple 1989
Acer grandidentatum	Nutt.	Aceraceae	bigtooth maple			N	0	0	0	1	1	0	0	0	1	0	1	Davis & Wilhour 1976; Treshow & Stewart 1973
Acer negundo	L.	Aceraceae	boxelder			N/X	1	1	1	0	1	1	1	0	1	0	1	Davis & Wilhour 1976; Treshow & Stewart 1973
Amelanchier alnifolia	Nutt.	Rosaceae	serviceberry	X	X	X	0	0	1	0	1	1	1	1	1	0	1	Davis & Wilhour 1976; Mavity et al. 1995; Treshow & Stewart 1973
Arctostaphylos uva-ursi	(L.) Spreng.	Ericaceae	red bearberry			X	0	1	0	1	0	0	0	0	0	0	0	Tingey et al. 1976a
Artemisia tridentata	Nutt.	Asteraceae	big sagebrush		N	X	1	1	1	1	1	1	1	1	1	1	1	Davis & Wilhour 1976; Treshow & Stewart 1973;
Artemisia sp.		Asteraceae		X														Mavity et al. 1995
Cercis canadensis		Fabaceae	redbud			X	0	0	0	0	0	0	1	0	0	0	0	Wood & Coppolino 1971
Chilopsis linearis	(Cav.) Sweet	Bignoniaceaea	desert willow	N	N		0	0	0	0	0	0	1	0	0	0	0	Temple 1989
Gleditsia triacanthos	L.	Fabaceae	honey-locust			X	0	0	0	0	0	0	0	0	0	0	1	Davis & Wilhour 1976; Treshow 1970; Wood & Coppolino 1971
Mahonia repens	G.Don	Berberidaceae	Oregon grape			N	1	0	1	1	0	0	0	0	1	0	1	Davis & Wilhour 1976; Treshow & Stewart 1973;
Physocarpus monogynus		Rosaceae	mountain ninebark	X			0	0	0	0	0	0	0	1	0	0	0	Mavity et al. 1995
Picea pungens	Engelm.	Pinaceae	blue spruce			X	0	1	1	1	0	0	1	1	0	0	0	Davis & Wilhour 1976; Treshow 1970
Picea engelmannii	Parry ex Engelm.	Pinaceae	Engelmann spruce	N			0	1	1	1	0	0	1	1	0	0	0	Bytnerowicz & Grulke 1992

Table 2-1 continued				Ozone (ppb) N=not sensitive X=sensitive			ARCH	BAND	BLCA	BRCA	CANY	CARE	GRCA	GRSA	MEVE	PEFO	ZION	
Species	Authority	Family	Common name	0-120	121-200	>200												References
Pinus ponderosa var scopulorum	Engelm.	Pinaceae	ponderosa pine			X	0	1	1	1	1	1	1	1	1	0	1	Aitken et al. 1984
Pinus ponderosa var ponderosa	Laws.	Pinaceae	ponderosa pine	N	X	X	0	0	0	0	0	0	0	0	0	0	0	Benes et al. 1995; Beyers et al. 1992; Bytnerowicz et al. 1989; Bytnerowicz et al. 1990; Bytnerowicz & Grulke 1992; Davis 1977; Evans & Miller 1972; Fenn et al. 1995; Miller et al. 1963, 1969, 1983; Peterson & Arbaugh 1988; Pye 1988; Richards et al. 1968; Temple et el. 1992, 1993; Temple & Miller 1994; Tingey et al. 1976a,b
Populus tremuloides	Michx.	Salicaceae	quaking aspen	X	X	X	0	1	1	1	1	0	1	1	1	0	1	Berrang et al. 1986, 1991; Coleman et al. 1995a,b; Davis & Wilhour 1976; Greitner et al. 1994; Karnosky 1976; Karnosky & Witter 1992; Pell et al. 1995; Pye 1988; Treshow 1970; Treshow & Stewart 1973; Wang et al. 1986
Potentilla fruticosa	L.	Rosaceae	golden hardhack		N	X	0	0	1	1	0	0	1	1	0	0	0	Treshow & Stewart 1973
Prunus virginiana		Rosaceae	choke cherry	X			0	1	1	1	1	0	1	1	1	0	1	Mavity et al. 1995
Pseudotsuga menziesii	(Mirb.) Franco	Pinaceae	Douglas-fir	N/X	N	N/X	0	1	1	1	1	1	1	1	1	0	1	Davis & Wood 1972; Gorissen et al. 1994; Gorissen et al. 1991a,b; Gorissen & Van Veen 1988; Martin et al. 1988; Pye 1988; Smeulders et al. 1995; Wilhour & Neely 1977; Bytnerowicz & Grulke 1992
Quercus gambelii	Nutt.	Fagaceae	Gambel oak		N	X	0	1	1	1	1	1	1	0	1	0	1	Treshow & Stewart 1973
Rhus trilobata	Nutt. ex T. & G.	Anacardiaceae	squawberry	X	X		0	1	1	1	0	1	1	1	0	1	1	Temple 1989

Species	Authority	Family	Common name	Ozone (ppb) N=not sensitive X=sensitive			ARCH	BAND	BLCA	BRCA	CANY	CARE	GRCA	GRSA	MEVE	PEFO	ZION	References
				0-120	121-200	>200												
Rosa woodsii	Lindl.	Rosaceae	Woods' rose	N	X		1	0	1	1	1	1	1	1	1	0	1	Davis & Wilhour 1976; Treshow & Stewart 1973

Table 2-1, continued

Species	Authority	Family	Common name	Ozone (ppb) N=not sensitive X=sensitive			ARCH	BAND	BLCA	BRCA	CANY	CARE	GRCA	GRSA	MEVE	PEFO	ZION	References
				0-120	121-200	>200												
Rubus parviflorus		Rosaceae	thimbleberry	X/N	X/N		0	1	0	0	0	0	1	0	0	0	0	Mavity et al. 1995; Hogsett (unpubl)
Sambucus racemosa		Caprifoliaceae	red berried elder	N	N		0	0	1	0	0	0	1	1	0	0	1	Mavity et al. 1995; Hogsett (unpubl); Brace et al. (unpubl)
Salix gooddingii	Ball.	Salicaceae	Goodding's willow	N	X		0	0	0	0	1	0	1	0	0	0	1	Temple 1989
Toxicodendron radicans	(L.) Kuntze	Anacardiaceae	eastern poison ivy		N	X	0	0	1	0	0	1	0	0	1	0	0	Davis & Wilhour 1976; Treshow & Stewart 1973;
Vaccinium sp.				X														Mavity et al. 1995

Aspen

Most studies of ozone exposure on aspen have found that aspen is more sensitive than most tree species, with effects developing with peak exposures of < 120 ppb. Ozone effects on photosynthesis and growth of aspen occur below concentrations required to produce chlorotic flecking or mottling on leaves. W. Hogsett (unpublished data) found that biomass of aspen seedlings was reduced by about 10% for ozone exposures totaling 5000 to 55,000 ppb-hour per year by the Sum60 criteria (12 hr/day for 92 days), with a strong effect of genotype. A 30% loss of growth developed between levels of cumulative exposure of 15,000 ppb-hr and 70,000 ppb-hr. Based on these Sum60 values, some loss of aspen growth may be occurring in Class I areas of the Colorado Plateau, although most varieties tested were from the Great Lakes region.

Coleman et al. (1995a,b) exposed 3 clones of aspen to 3 levels of ozone in open-topped chambers. The ozone levels included charcoal filtered air (maximum peak concentration of 34 ppb), an "ambient" treatment representing conditions in the Great Lakes region (where peak concentrations exceed 70 ppb), and twice ambient (peak values over 140 ppb). Over the 2-year study, exposure to ambient ozone lowered the growth (biomass) of the most sensitive clone by about 40%, with little effect on the 2 less-sensitive clones. At twice ambient ozone, growth of the most-sensitive clone declined slightly below the ambient treatment; the intermediate clone declined by about 25% relative to the charcoal-filter treatment, and the least sensitive clone appeared to decline in whole-plant photosynthesis but not in growth.

Greitner et al. (1994) examined the effects of ozone exposure in relation to drought stress and N supply. The ozone exposures included a control of charcoal filtered air (with ozone concentrations of about 25 to 35 ppb), and an "ambient" treatment to mimic Pennsylvania conditions of about 80 ppb ozone. Exposure to the 80 ppb treatment reduced seedling carbon gain (which should index growth) by about 20 to 30% regardless of water treatment or N treatment.

Karnosky (1976) exposed cuttings of aspen clones to various levels of ozone; 3 of the 5 clones showed some visible injury to leaves when exposed to levels of ozone as low as 50 ppb, and a fourth clone showed injury at 100 ppb. In a more recent study, Karnosky and Witter (1992) found that ozone exposure of 80 ppb produced visible injury to leaves, but no effect on seedling growth; fertilization with N substantially increased growth regardless of ozone exposure.

Pell et al. (1995) also found that N supply strongly affected the sensitivity of aspen to ozone exposures of about 75 ppb; stresses from too little to too much N prevented any injury from ozone, whereas seedlings with adequate N supply showed less growth when exposed to ozone.

Wang et al. (1986) performed an ozone exposure experiment for 3 years with aspen saplings in open topped chambers. One set of chambers received only charcoal filtered air, and the other ambient air with peak concentrations exceeding 120 ppb between 1 and 6 times each year (mean hourly values averaged about 60 ppb for the growing seasons). Sapling growth was reduced by about 12 to 24%, depending on the sensitivity of the clones. Only one of the 5 clones tested showed visible injury to leaves, even though all clones showed reduced growth with exposure to ambient ozone.

We conclude that evidence from ozone exposure studies indicates that aspen injury by ozone is possible under current ozone concentrations on the Colorado Plateau. No reports have been made of visible injury to leaves, nor of any unexpected growth reductions. This absence of evidence of any ozone impacts may indicate no impacts occur, but the lack of extensive study on the Colorado Plateau leaves open the possibility of unrecorded impacts.

Douglas-fir

The evidence for ozone sensitivity of Douglas-fir is more mixed than for aspen. A series of carbon dioxide ($^{14}CO_2$) experiments by Gorissen et al. (1991a, 1991b, 1994) and Smeulders et al. (1995) documented variable sensitivity of Douglas-fir seedlings and trees in the Netherlands to levels of ozone exposure from 50 to 120 ppb. These studies documented some effects on patterns of carbohydrate transport and storage (some gas exchange effects from their earlier studies could not be repeated in their later studies at the lowest ozone level), but were not designed to look for overall growth effects. No visible injury on foliage was found. Bytnerowicz and Grulke (1992) report unpublished results of N. Grulke on exposure of Douglas-fir, ponderosa pine, Engelmann spruce and white fir to 60-70 ppb ozone; no effects of ozone were found for any of the species. W. Hogsett (unpublished data) found that a 10% growth reduction in Douglas-fir required a Sum60 (12 hr/day for 92 days) exposure of 60,000 ppb-hr to 250,000 ppb-hr, which is far higher than current exposures for the Colorado Plateau. Ozone exposure studies indicate a possibility of physiologic effects on Douglas-fir below 120 ppb (perhaps as low as 60 ppb), but no substantial effects have been shown, and no reports of visible injury or growth reductions exist for the Colorado Plateau or for areas that are much more polluted.

Ponderosa Pine

Many studies have examined the sensitivity of ponderosa pine (and closely related Jeffrey pine) in the San Bernardino Mountains and Sierra Nevada of California. As early as the 1950s, chlorotic mottling was observed on ponderosa pine, and the condition was dubbed the "x-disease" (Miller 1992). Controlled exposure to ozone in the 1960s demonstrated that ozone caused the observed injury; mean ozone concentrations near Los Angeles in the 1970s were averaging near 100 ppb, with frequent peaks above 250 ppb. Many controlled exposure studies demonstrated sensitivity to high concentrations of ozone (> 200 ppb), such as Miller et al. (1983). High mortality of pines resulted from beetle attacks and root rot pathogens on ozone-injured trees. Farther north where ozone concentrations are lower (but still exceeding 100 ppb for 30 days or more), ponderosa pine with visible foliar injury show reduced growth (by an average of about 10%) relative to more resistant genotypes that show no injury (Peterson and Arbaugh 1992). However, Peterson and Arbaugh (1992) found no evidence of widespread growth reductions in recent decades.

Ozone concentrations are somewhat lower along the Front Range in Colorado, and no foliar injury on ponderosa pine (or other conifers) has been reported (Graybill et al.1992). The Rocky Mountain variety of ponderosa pine (var. *scopulorum*) may be less sensitive to ozone than the coastal subspecies (var. *ponderosa*). For example, Aitken et al. (1984) found that exposure of 2-yr-old seedlings of var. *scopulorum* to 250 ppb produced no visible injury, which is much higher than levels found to affect the coastal subspecies. However, we know of no exposure studies that compared the subspecies in the same experiment, so differences in protocols may account for some of the apparent differences in sensitivity.

No major growth changes are evident for forests of the Front Range, although a few of the stands examined by Graybill and by Peterson and Arbaugh could be interpreted as having some unusual growth declines at some point in recent decades. In southern Arizona, Graybill and Rose (1992) reported some anomalously low growth rates in several of the ponderosa pine stands they examined. They suggested that the absence of growth rings and reduction in width of growth rings could reflect stand dynamics associated with the aging of stands that were established in the wet period of 1900 to 1920, or could result from some air-borne pollutant. No visible injury was observed by Graybill and Rose (1992).

W. Hogsett (unpublished data) found that a 10% growth reduction for ponderosa pine may develop with cumulative ozone exposures (Sum60 with 12 hr/day for 92 days) of 15,000 ppb-hr to 55,000 ppb-hr. Both the Grand Canyon and Bandelier have experienced levels overlapping the

lower end of this range. The evidence is strong that ponderosa pine in southern California have been affected by regional levels of ozone, but no evidence of any impact is available for the Colorado Plateau.

Shrubs

Much less work has focused on the potential effects of ozone on shrubs than on trees (Table 2-1). Temple (1989) exposed a variety of species in Joshua Tree National Park to levels of ozone from about 50 to 200 ppb, and also conducted some comparisons of plant performance in ambient- and charcoal-filtered air in Riverside, California. Squawbush (*Rhus trilobata*) was the most sensitive species, showing no visible injury at 50 ppb, slight injury at 100 ppb, and greater than 10% foliar injury at 150 ppb and above. Shrubs grown in charcoal filtered air had no sign of visible injury, but they also grew less than plants exposed to the full ambient level of ozone (about 75 ppb) in Riverside. Temple (1989) concluded that *Rhus trilobata* may be a useful species for indicating ozone levels; foliar injury might appear at levels near 100 ppb, even though the plants may show no growth decline (or even an increase) at these levels.

Research reported in an unpublished report from the USDA Forest Service Center for Forest Environmental Studies (Mavity et al. 1995) sought to find shrub species that might be sensitive indicators of ozone pollution in the West.   A variety of species were exposed in a chamber for about a month to three levels of ozone: low = average of 25 ppb (50 ppb maximum), medium = average of 55 ppb (80 ppb maximum), and high = average of 75 ppb (120 ppb maximum). These shrub seedlings were relatively small, with weights of < 10 g, and heights of <10 cm, so extrapolation of the results to juvenile and mature shrubs is problematic. The results of these investigations are described below.

Ninebark (*Physocarpus monogynus*) was relatively sensitive to ozone; the average leaf weight/shrub declined by 25% from the low to the moderate ozone exposure, and stem weight declined by about 15% (which was not statistically significant). About a third of the individuals exposed to the medium ozone level showed some defoliation, brown necrosis and red stippling of leaves (but little chlorotic mottling).

Choke cherry (*Prunus virginiana*) was less sensitive to ozone exposure, showing no effect of the medium level on plant weight, and only moderate stippling, necrosis and mottling of some leaves.

Serviceberry (*Amelanchier alnifolia*) appeared to decrease in photosynthesis rates with the medium ozone exposure, although the effect was not statistically significant. Stem weight was not

affected by ozone exposure, although leaf drop increased substantially at the high ozone level. Mavity et al. (1995) concluded that *Amelanchier* would not be a useful indicator of ozone exposure levels because of only minor development of visible symptoms.   Brace et al. (unpublished manuscript) exposed *Amelanchier alnifolia* seedlings to 60 days of ozone (with 126 ppb daily peaks and 20 ppb nightly minima), and found stippling on older foliage followed later by necrotic spots. Further work may be needed to determine the usefulness of *Amelanchier* as an indicator of ozone exposure.

Mavity et al. (1995) also exposed seedlings of *Artemisia* shrubs, but they didn't mention which species of *Artemisia* was used.   Photosynthesis and plant growth were both reduced at the medium ozone level; plants exposed to the medium level produced only about 75% the biomass of those in the low ozone treatment.   The major foliar symptom of ozone exposure was a curling of leaves, which Mavity et al. (1995) concluded would not be specific enough for use as an indicator of in-field ozone exposure.

Thimbleberry (*Rubus parviflorus*) shrubs were tested in two sets of exposures, one for small seedlings (< 1 g stem weight), and another for slightly larger individuals (up to 6 g stem weight). The smaller seedlings were very sensitive to the medium ozone exposure, producing just half the stem weight of the seedlings in the low-ozone treatment.   The smaller seedlings also showed a variety of visible injuries, but the authors concluded the symptoms may not be specific enough to ozone injury to have promise as a bioindicator.   The larger seedlings showed essentially no response to ozone treatment, except perhaps an increase in growth at the medium ozone level.   No visible injury developed on the larger seedlings.   This comparison of small and somewhat larger seedlings underscores the importance of differences in sensitivity with either life stage of development, or experimental protocols.

An unidentified species of elderberry (*Sambucus*) was also tested and found to show no response to ozone, with the exception of some chlorotic mottling at the highest ozone level.   An unidentified species of *Vaccinium* showed no response to ozone in terms of photosynthesis or growth, although the foliage did develop classic purple stippling. Mavity et al. (1995) concluded that *Vaccinium* species may have substantial promise for use as an indicator species, and they recommended more trials.

No evidence of visible injury or growth effects has been reported for field-grown shrubs in the Colorado Plateau.   Some controlled-exposure evidence indicates a potential for moderate sensitivity of some shrubs to moderate level of ozone, with sensitivity described as signs of visible injury or changes in growth of very young seedlings.

Grasses, Sedges, Forbs

Even less information is available on the ozone-sensitivity of non-woody vegetation on the Colorado Plateau (Table 2-2). Treshow and Stewart (1973) exposed over 70 species of common plants in the Intermountain West to concentrations of 150 ppb or higher by placing chambers over well-established plants in the field. Only a few species were affected at the minimum ozone level, and this minimum level was far greater than any concentrations of ozone that apply to the Colorado Plateau. Thompson et al. (1984) exposed 47 species of annual plants in the Mojave desert to 50 ppb or greater levels of ozone. A few species that are also present on the Colorado Plateau that were sensitive (based on visible injury) to exposures lower than 120 ppb were: *Camissonia claviformis, Cryptantha nevadensis, Malacothrix glabrata, Mentzelia albicaulis, Pectocarya heterocarpa* and *Pectocarya platycarpa*. Bytnerowicz et al. (1988) also tested the sensitivity of desert annuals to ozone. Only three species were sensitive to ozone (at levels of 120 ppb and above): *Camissonia claviformis, Camissonia hirtella*, and *Erodium cicutarium*; each of these species showed 1 to 3% injury to leaves, whether irrigated or not irrigated.

We conclude that no evidence currently indicates that species of grasses, sedges, or forbs show much sensitivity to ozone levels below 100 or 120 ppb. No reports of visible injury or other effects are available for the Class I NPS areas of the Colorado Plateau.

Table 2-2. Reported sensitivity of forbs, sedges, and grasses to ozone. N = not sensitive, X = sensitive by some measure, and blanks indicate no reported information. Species is absent (0) or present (1) in the park or monument.

Species	Authority	Family	Common name	Ozone (ppb) range N=not sensitive X=sensitive 0-120	121-200	>200	ARCH	BAND	BLCA	BRCA	CANY	CARE	GRCA	GRSA	MEVE	PEFO	ZION	References
Achillea millefolium	L.	Asteraceae	common yarrow		N	X	0	0	1	1	0	0	1	1	1	1	1	Treshow & Stewart 1973
Agastache urticifolia	(Benth.) Kuntze	Lamiaceae	nettle leaf giant hyssop		X	X	0	0	1	0	0	0	0	0	0	0	1	Treshow & Stewart 1973
Allium acuminatum	Hook.	Liliaceae	taper tip onion		N	X	0	0	1	1	0	0	1	0	1	0	1	Treshow & Stewart 1973
Ambrosia psilostachya	DC.	Asteraceae	western ragweed		N	N	0	0	0	0	0	0	1	0	1	0	0	Treshow & Stewart 1973
Angelica pinnata	S.Wats.	Apiaceae	small leaf angelica		N	X	0	0	0	1	0	0	0	0	0	0	0	Treshow & Stewart 1973
Baileya pleniradiata		Asteraceae	woolly desert marigold	N		N	0	0	0	0	0	0	0	0	0	0	1	Thompson et al. 1984
Bromus carinatus	Hook. & Arn.	Poaceae	California brome		N	X	1	0	1	1	0	0	0	0	1	0	1	Treshow & Stewart 1973
Bromus rubens		Poaceae	foxtail brome	N		X	0	0	0	0	0	1	0	0	0	1	1	Thompson et al. 1984
Bromus tectorum	L.	Poaceae	cheat grass		X	X	1	0	1	1	1	1	1	1	1	1	1	Treshow & Stewart 1973
Calochortus nuttallii	Torr.	Liliaceae	sego lily		N	N	1	1	0	1	1	1	1	0	1	0	1	Treshow & Stewart 1973
Camissonia claviformis	(Torr. & Frem.) Raven	Onagraceae	brown eyes	X	X	X	0	0	0	0	0	0	1	0	0	0	0	Bytnerowicz et al. 1988; Thompson et al. 1984
Carex siccata	Dewey	Cyperaceae			N	X	1	0	0	0	0	0	0	0	0	0	0	Treshow & Stewart 1973
Caulanthus cooperi		Brassicaceae	Cooper's wild cabbage	N	N	X	0	0	0	0	0	0	1	0	0	0	0	Bytnerowicz et al. 1988; Thompson et al. 1984
Chaenactis fremontii		Asteraceae	morning bride	N		X	0	0	0	0	0	1	1	0	0	0	0	Thompson et al. 1984
Chaenactis stevioides		Asteraceae	broad-flower pincushion	N	N	X	1	0	0	0	1	0	1	0	0	1	1	Bytnerowicz et al. 1988; Thompson et al. 1984
Chenopodium fremontii	Wats.	Chenopodiaceae	Fremont's goosefoot		N	X	1	0	1	1	1	1	1	1	1	1	1	Treshow & Stewart 1973
Chorizanthe brevicornus		Polygonaceae	brittle spine flower	N		X	0	0	0	0	0	0	1	0	0	0	0	Thompson et al. 1984
Cichorium intybus	L.	Asteraceae	chicory		N	X	0	0	0	0	0	0	1	0	1	0	1	Treshow & Stewart 1973

Table 2-2 continued

Species	Authority	Family	Common name	Ozone (ppb) range N=not sensitive X=sensitive			ARCH	BAND	BLCA	BRCA	CANY	CARE	GRCA	GRSA	MEVE	PEFO	ZION	References
				0-120	121-200	>200												
Cirsium arvense	(L.) Scop.	Asteraceae	Canadian thistle		N	X	0	0	1	0	0	0	0	0	1	0	0	Treshow & Stewart 1973
Collomia linearis	Nutt.	Polemoniaceae	narrowleaf mountain trumpet		N	X	0	0	1	0	0	0	1	0	1	0	0	Treshow & Stewart 1973
Conium maculatum	L.	Apiaceae	poison hemlock		N	X	0	0	0	0	0	0	1	0	0	0	0	Treshow & Stewart 1973
Cryptantha angustifolia		Boraginaceae	panamint cat's eye	N	N	X	0	0	0	0	0	0	1	0	0	0	0	Bytnerowicz et al. 1988; Thompson et al. 1984
Cryptantha circumscissa		Boraginaceae	cushion cat's eye	N		X	0	0	0	0	0	1	1	0	0	0	0	Thompson et al. 1984
Cryptantha micrantha		Boraginaceae	red root cat's eye	N		X	0	0	0	0	0	0	1	0	0	0	1	Thompson et al. 1984
Cryptantha nevadensis		Boraginaceae	Nevada cat's eye	X		X	0	0	0	0	0	0	1	0	0	0	0	Thompson et al. 1984
Cryptantha pterocarya		Boraginaceae	wing-nut cat's eye	N	N	X	0	0	1	0	0	1	1	0	0	0	1	Bytnerowicz et al. 1988; Thompson et al. 1984
Descurainia californica	(Gray) O.E.Schultz	Brassicaceae	Sierran tansy mustard		N	X	0	0	0	0	0	0	1	0	0	0	0	Treshow & Stewart 1973
Descurainia pinnata		Brassicaceae	western tansy mustard	N		X	1	1	1	0	1	1	1	1	1	1	0	Thompson et al. 1984
Epilobium augustifolium	L.	Onagraceae	fireweed		N	X	0	0	1	1	0	0	1	1	0	0	1	Treshow & Stewart 1973
Erodium cicutarium		Geraniaceae	red-stem stork's bill	N/X	X	X	0	1	1	0	1	1	1	0	1	1	1	Bytnerowicz et al. 1988; Thompson et al. 1984
Eucrypta micrantha		Hydrophyllaceae	dainty desert hideseed	N		X	0	0	0	0	0	0	1	0	0	0	0	Thompson et al. 1984
Festuca octoflora		Poaceae	8flower 6weeks grass	N	N	N	0	1	0	1	1	0	0	0	1	0	1	Bytnerowicz et al. 1988; Thompson et al. 1984
Galium bifolium	Wats.	Rubiaceae	twin leaf bedstraw		N	X	0	0	1	0	0	0	1	0	0	0	1	Treshow & Stewart 1973
Gayophytum racemosum	T. & G.	Onagraceae	black foot groundsmoke		N	X	0	0	0	1	0	0	0	0	0	0	0	Treshow & Stewart 1973
Gentiana amarella	L.	Gentianaceae	autumn dwarf gentian		X	X	0	0	0	1	0	0	0	0	0	0	0	Treshow & Stewart 1973

Table 2-2 continued

Species	Authority	Family	Common name	Ozone (ppb) range N=not sensitive X=sensitive			ARCH	BAND	BLCA	BRCA	CANY	CARE	GRCA	GRSA	MEVE	PEFO	ZION	References
				0-120	121-200	>200												
Geranium fremontii	Torr.	Geraniaceae	purple cluster crane's bill		N	X	0	0	0	1	0	0	1	1	0	0	0	Treshow & Stewart 1973
Geranium richardsonii	Fisch. & Traut.	Geraniaceae	white crane's bill		X	X	0	0	1	1	0	0	1	0	0	0	0	Treshow & Stewart 1973
Hedysarum boreale	Nutt.	Fabaceae	boreal sweet vetch		X	X	0	0	0	1	1	1	0	0	1	0	0	Treshow & Stewart 1973
Helianthus annuus	L.	Asteraceae	common sunflower		N	X	0	1	1	1	1	1	1	0	1	1	1	Treshow & Stewart 1973
Juncus sp.					N	X												Treshow & Stewart 1973
Langloisia schottii		Polemoniaceae	Schott's calico	N		X	0	0	0	0	0	0	1	0	0	0	0	Thompson et al. 1984
Lathyrus lanszwertii	Kell.	Fabaceae	Nevada vetchling		N	X	0	0	1	0	0	0	1	0	0	0	1	Treshow & Stewart 1973
Lathyrus pauciflorus	Fern.	Fabaceae	few flower vetchling		N	X	0	0	0	0	0	0	0	0	1	0	0	Treshow & Stewart 1973
Lepidium lasiocarpum		Brassicaceae	hairy-pod pepperwort	N		N	0	0	0	0	0	0	1	0	0	0	1	Thompson et al. 1984
Lolium perenne	L.	Poaceae	perennial rye grass		X		0	1	0	1	0	0	1	0	1	1	0	Nussbaum et al. 1995
Lupinus concinnus		Fabaceae		N	N	X	0	0	0	0	0	0	0	0	0	0	1	Bytnerowicz et al. 1988; Thompson et al. 1984
Lupinus sp.		Fabaceae				X												Tingey et al. 1976a
Malacothrix glabrata		Asteraceae	smooth desert dandelion	X		X	0	0	0	0	0	1	1	0	0	0	0	Thompson et al. 1984
Medicago sativa	L.	Fabaceae	alfalfa		N/X	X	1	1	0	1	1	1	1	0	1	1	1	Hill et al. 1961; Treshow 1970; Treshow & Stewart 1973
Mentzelia albicaulis		Loasaceae	white stem blazingstar	X		X	1	0	0	0	1	1	1	1	1	1	1	Thompson et al. 1984
Mertensia arizonica	Greene	Boraginaceae	aspen bluebells		N	X	0	0	1	1	0	0	0	0	0	0	1	Treshow & Stewart 1973
Mimulus guttatus	DC.	Scrophulariaceae	seep monkey		N	X	1	0	0	1	0	1	1	0	0	0	1	Treshow & Stewart 1973

flower

Table 2-2 continued

Species	Authority	Family	Common name	Ozone (ppb) range N=not sensitive X=sensitive			ARCH	BAND	BLCA	BRCA	CANY	CARE	GRCA	GRSA	MEVE	PEFO	ZION	References
				0-120	121-200	>200												
Osmorhiza occidentalis	Torr.	Apiaceae	sierran sweet cicely		N	X	0	0	1	0	0	0	0	0	0	0	1	Treshow & Stewart 1973
Pectocarya heterocarpa		Boraginaceae	chuckwalla combseed	X		X	0	0	0	0	0	0	1	0	0	0	0	Thompson et al. 1984
Pectocarya platycarpa		Boraginaceae	broad fruit combseed	X		X	0	0	0	0	0	0	1	0	0	0	0	Thompson et al. 1984
Perityle emoryi		Asteraceae	emory's rockdaisy	N		N	0	0	0	0	0	0	1	0	0	0	0	Thompson et al. 1984
Phacelia heterophylla	Pursh	Hydrophyllaceae	variable leaf scorpion weed		N	X	0	0	0	0	0	0	0	0	1	0	1	Treshow & Stewart 1973
Plantago insularis		Plantaginaceae	blond plantain	N	N	X	0	0	0	0	0	0	1	0	0	0	0	Bytnerowicz et al. 1988; Thompson et al. 1984
Poa annua	L.	Poaceae	annual bluegrass		N	X	0	1	0	0	0	0	1	0	1	0	0	Hill et al. 1961
Poa pratensis	L.	Poaceae	Kentucky blue grass		N	X	1	0	0	1	0	1	1	1	1	1	1	Treshow & Stewart 1973
Polemonium foliosissimum	A.Gray	Polemoniaceae	towering jacob's ladder		N	X	0	0	0	0	0	0	0	1	1	0	0	Treshow & Stewart 1973
Polygonum douglasii	Greene	Polygonaceae			N	X	0	0	1	1	0	0	1	0	1	0	1	Treshow & Stewart 1973
Rumex crispus	L.	Polygonaceae	curly dock		N	X	0	1	1	1	0	1	1	0	1	0	1	Treshow & Stewart 1973
Salvia columbariae		Lamiaceae	California sage	N	N	X	0	0	0	0	0	0	1	0	0	0	1	Bytnerowicz et al. 1988; Thompson et al. 1984
Sphaeralcea ambigua		Malvaceae	apricot globe mallow	N		N	0	0	0	0	0	1	1	0	0	1	1	Thompson et al. 1984
Stephanomeria exigua		Asteraceae	white plume wire lettuce	N		X	1	0	0	0	1	1	1	0	0	1	1	Thompson et al. 1984
Streptanthella longirostris		Brassicaceae	long beak fiddle mustard	N		X	1	0	0	0	1	1	1	0	0	1	1	Thompson et al. 1984

Species	Authority	Family	Common name	0-120	121-200	>200	ARCH	BAND	BLCA	BRCA	CANY	CARE	GRCA	GRSA	MEVE	PEFO	ZION	References
Taraxacum officinale	Wiggers	Asteraceae	common dandelion		N	X	1	0	1	1	1	1	1	1	1	0	1	Treshow & Stewart 1973

Table 2-2 continued

Ozone (ppb) range
N=not sensitive
X=sensitive

Species	Authority	Family	Common name	0-120	121-200	>200	ARCH	BAND	BLCA	BRCA	CANY	CARE	GRCA	GRSA	MEVE	PEFO	ZION	References
Thalictrum fendleri	Engelm.	Ranunculaceae	Fendler's meadow rue		N	X	0	0	0	1	0	0	1	0	1	0	1	Treshow & Stewart 1973
Thysanocarpus curvipes		Brassicaceae	sand fringepod	N	N	X	0	0	0	0	0	0	1	0	0	0	1	Bytnerowicz et al. 1988; Thompson et al. 1984
Trifolium repens	L.	Fabaceae	white clover	X	X	X	0	1	1	1	0	1	1	1	1	0	1	Blum et al. 1982; Cooley & Manning 1987; Karlsson et al. 1995; Letchworth & Blum 1977; Nussbaum et al. 1995; Reich & Amundson 1985
Urtica gracilis	Ait.	Urticaceae	stinging nettle		N	X	0	1	0	0	0	0	0	0	0	0	0	Treshow & Stewart 1973
Veronica anagallis-aquatica	L.	Scrophulariaceae	blue water speedwell		N	X	0	0	1	0	0	1	1	0	1	0	0	Treshow & Stewart 1973
Vicia americana	Muhl.	Fabaceae	American purple vetch		N	N/X	0	1	1	1	0	1	1	1	1	0	1	Treshow & Stewart 1973
Viguiera deltoidea		Asteraceae	triangle goldeneye	N		N	0	0	0	0	0	0	1	0	0	0	0	Thompson et al. 1984
Viola adunca	Sm.	Violaceae	hook spur violet		N	X	0	0	1	1	0	0	1	0	1	0	0	Treshow & Stewart 1973

Lichens

Surprisingly little work has been done on the sensitivity of lichens to ozone. Lichens are generally regarded as sensitive indicators of air pollution because they lack stomates and are more tightly coupled to the atmosphere (Nash and Wirth 1988). Patterns of lichen abundance around point sources of pollution have pointed to non-ozone pollutants, particularly SO_2, as the major agent damaging lichens. For example, McCune (1988) examined the patterns of lichen abundance with distance from Indianapolis, Indiana, and found that lichen patterns correlated relatively well with gradients of SO_2 concentrations but not with ozone concentrations. A few studies have fumigated lichens with ozone. Eversman and Sigel (1987) reported that fumigation with just 30 ppb of ozone reduced photosynthesis of some lichens; however, it is not clear that their "no ozone" level would have acheived lower ozone concentrations given that background levels are usually higher than this level (particularly in eastern Tennessee). Other fumigation studies, such as the one by Nash and Sigal (1979), exposed lichens to concentrations of ozone that were far higher than ambient conditions (such as 500 ppb), providing no insights for field conditions. We found only one study that used realistic levels of ozone fumigation. Scheidegger and Schroeter (1995) exposed several species (including *Hypogymnia bitteri*, which occurs in Bandelier NM) to 40 ppb ozone at night and 90 ppb ozone in the day, and found 4% to 40% reductions in chlorophyll concentrations relative to the control treatment. Indirect evidence of lichen sensitivity to ozone comes from Sigal and Nash (1983) who transplanted *Hypogymnia enteromorpha* into "clean" and "high ozone" areas of the Los Angeles basin, and the lichens in the high ozone area had greater degradation of the thalli.

Peterson et al. (1992) developed a list of California lichens that are sensitive to various levels of ozone exposure, from < 20 ppb (growing season 7-hr mean) to >70, and these sensitivity ratings were used by Eilers et al. (1994) to infer lichen sensitivity for Class I NPS areas of the Pacific Northwest. These ratings are inferred from patterns of lichen distribution in the Los Angeles Basin, and an assumption that ozone is the primary factor controlling lichen distribution. In the absence of experimental exposures of lichens to ozone, there is no basis for judging the likely validity of these assumptions. It is also difficult to see how species that are sensitive to concentrations of less than 20 ppb could have evolved given that pre-industrial concentrations of ozone were likely higher than this (EPA 1996).

Sulfur Dioxide

Trees and Shrubs

   Trees are generally thought to be insensitive to ambient concentrations of sulfur dioxide. Most experiments with controlled exposures of tree seedlings to SO_2 used concentrations that were far too high to be interpretable for field conditions (e.g. Davis and Wilhour 1976). Ponderosa and pinyon pines are the only tree species from the Colorado Plateau that have been included in fumigation studies. Leininger (1991) reported that 60 days of exposure to 35 ppb SO_2 reduced needle weight and diameter of ponderosa pine seedings. Kärenlampi and Houpis (1986) found that fumigation with 75 ppb of SO_2 caused browning of needle tips. Some other studies have found less effect; Hogsett et al. (1989) found variable effects of SO_2 fumigation on measures of plant growth for ponderosa pine, including stimulation of bud elongation by levels of SO_2 on the order of 30 ppb. Trujillo et al. (1993) exposed pinyon pine seeds, germinants, and 1-yr-old seedlings to SO_2. Their minimum level was 200 ppb, which is 2 orders of magnitude or more beyond ambient levels in pinyon pine's range; however, no effects were seen on growth or biomass unless extremely severe exposures of 3000 ppb or higher were used.

   All of the pine studies used concentrations of SO_2 that are many times higher than levels found on the Colorado Plateau, so we conclude there is no cause for concern about direct effects of SO_2 exposure on plants in this area.

Table 2-3. Reported sensitivity of vascular plants and lichens to SO_2. N = not sensitive, X = sensitive by some measure. Species is absent (0) or present (1) in the park or monument.

Species	Authority	Family	Common name	SO₂ at <50ppb N= not sensitive X = sensitive	ARCH	BAND	BLCA	BRCA	CANY	CARE	GRCA	GRSA	MEVE	PEFO	ZION	References
Grasses, forbs, trees																
Agropyron smithii	Rydb.	Poaceae	western wheatgrass	X	0	1	1	1	0	1	1	1	1	1	0	Lauenroth et al. 1985
Agropyron spicatum		Poaceae		N	0	0	0	1	0	0	0	0	0	0	0	Runeckles et al. 1981
Lolium perenne	L.	Poaceae	perennial rye grass	N	0	1	0	1	0	0	1	0	1	1	0	Runeckles et al. 1981
Pinus edulis	Engelm.	Pinaceae	pinyon pine	N	1	1	1	1	1	1	1	1	1	0	1	Trujillo et al. 1993
Pinus ponderosa	Laws.	Pinaceae	ponderosa pine	X/N	0	1	1	1	1	1	1	1	1	0	1	Leininger 1991;Kärenlampi & Houpis 1986; Hogsett et al. 1989
Pseudotsuga menziesii	(Mirb.) Franco	Pinaceae	Douglas-fir	X/N	0	1	1	1	1	1	1	1	1	0	1	Gorrisen & Van Veen 1988; Runeckles et al. 1981
Lichen Species																
Buellia sp.				X	0	1	0		1	1	1	0	1	1	1	Vick & Bevan 1976
Buellia alboatra	(Hoffm.) Brauth and Rostr.			X	0	0	0		0	0	0	0	0	0	1	Hawksworth & Rose 1970; Wetmore 1983
Buellia punctata	(Hoffm.) Mass.			X/N	0	1	0		0	1	1	0	1	1	1	Hawksworth & Rose 1970; Johnsen & Sochting 1973; Wetmore 1983; Will-Wolf 1980
Caloplaca aurantiaca				X	0	1	0		0	0	0	0	0	0	0	Hawksworth & Rose 1970
Caloplaca cerina	(Ehrh. ex Hedwig) Th. Fr.			X	0	0	0		0	1	1	0	1	1	1	Hawksworth & Rose 1970; Wetmore 1983
Candelaria concolor	(Dicks.) Stein			X/N	0	1	0		0	0	1	0	0	0	1	Hawksworth & Rose 1970; Wetmore 1983; Will-Wolf 1980; Johnson 1979
Candelariella vitellina	(Ehrh.) Mull.			X	0	1	0		0	1	1	0	1	1	1	Wetmore 1983
Candelariella	(Ach.) Lettau.			X	0	0	0		0	1	1	0	0	0	1	Wetmore 1983

xanthostigma

| *Cladonia sp.* | | | | X | 0 | 1 | 0 | | 0 | 1 | 1 | 0 | 1 | 0 | 1 | Vick & Bevan 1976 |

Table 2-3, continued.

Lichens	Authority	Family	Common name	SO$_2$ at < 50 ppb N = not sensitive X = sensitive	ARCH	BAND	BLCA	BRCA	CANY	CARE	GRCA	GRSA	MEVE	PEFO	ZION	References
Cladonia balfourii				X	0	0	0		0	0	0	0	1	0	1	Johnson 1979
Cladonia chlorophaea				X	0	0	0		0	1	1	0	0	0	1	Johnson 1979
Cladonia coniocraea	auct. (fide Ahti)			X	0	1	0		0	0	1	0	0	0	0	Wetmore 1983
Cladonia fimbriata	(L.) Fr.			X	0	1	0		0	0	1	0	1	0	0	Wetmore 1983
Collema tenax	(Sw.) Ach.			X	1	1	0		1	1	1	0	1	1	1	Sheridan 1979
Hypogymnia physodes	(L.) Nyl.			X/N	0	1	0		0	0	0	0	0	0	0	Hawksworth & Rose 1970; Holopainen & Karenlampi 1984; Johnsen & Sochting 1973; Rose & Hawksworth 1981; Vick & Bevan 1976; Johnson 1979
Lecanora carpinea	(L.) Vainio			X	0	0	0		0	1	0	0	1	0	0	Johnsen & Sochting 1973
Lecanora chlarotera	Nyl.			X	0	1	0		0	0	0	0	0	0	1	Hawksworth & Rose 1970; Wetmore 1983
Lecanora dispersa	(Pers.) Sommerf.			N	0	0	0		0	0	1	0	1	1	1	LeBlanc & Rao 1973; Vick & Bevan 1976; Wetmore 1983
Lecanora hagenii	(Ach.) Ach.			N/X	0	0	0		0	0	1	0	1	0	1	Wetmore 1983; Johnson 1979
Lecanora muralis	(Schreber) Rabenh.			N	0	1	0		0	1	1	0	1	1	1	Vick & Bevan 1976; Wetmore 1983
Lecanora saligna	(Schr.) Zahlbr.			X	0	1	0		0	1	1	0	1	0	1	Wetmore 1983
Lecidea sp.				X	0	1	0		0	1	1	0	1	1	1	Sheridan 1979
Lepraria incana	(L.) Ach.			X/N	0	0	0		0	0	1	0	1	0	0	Hawksworth & Rose 1970; Johnsen & Sochting 1973; Wetmore 1983
Lobaria scrobiculata				X	0	1	0		0	0	0	0	0	0	0	Hawksworth & Rose 1970
Pannaria sp.				X	0	1	0		0	0	1	0	0	0	1	Hawksworth & Rose 1970
Parmelia sp.				X	0	1	0		0	0	1	0	0	0	1	Vick & Bevan 1976
Parmelia olivacea				X	0	0	0		0	0	1	0	1	0	0	Wetmore 1983

Lichens	Authority	Family	Common name	SO$_2$ at < 50 ppb N = not sensitive X = sensitive	ARCH	BAND	BLCA	BRCA	CANY	CARE	GRCA	GRSA	MEVE	PEFO	ZION	References
Parmelia subargentifera	Nyl.			X	0	0	0		0	0	0	0	0	0	1	Wetmore 1983

Table 2-3, continued.

Lichens	Authority	Family	Common name	SO$_2$ at < 50 ppb N = not sensitive X = sensitive	ARCH	BAND	BLCA	BRCA	CANY	CARE	GRCA	GRSA	MEVE	PEFO	ZION	References
Parmelia sulcata	Tayl.			X/N	0	1	0		0	0	0	0	0	0	0	Hawksworth & Rose 1970; LeBlanc & Rao 1973; Rose & Hawksworth 1981; Will-Wolf 1980; Von Arb & Brungold 1990; Von Arb et al. 1990; Johnson 1979
Phaeophyscia orbicularis	(Necker) Moberg			X	1	1	0		0	0	1	1	1	0	1	Wetmore 1983
Physcia adscendens	(Fr.) H. Olivier.			X	0	1	0		0	1	1	0	1	0	1	Hawksworth & Rose 1970; Johnsen & Sochting 1973; Wetmore 1983
Physcia aipolia	(Ehrh.) Hampe			X	0	1	1		0	0	1	1	0	0	1	Hawksworth & Rose 1970; Wetmore 1983
Physcia dubia	(Hoffm.) Lett.			X	0	1	0		0	1	1	0	1	1	1	Johnsen & Sochting 1973
Physcia orbicularis	(Neck.) Poetsch			X	0	0	0		0	0	0	0	0	0	1	Hawksworth & Rose 1970; Johnsen & Sochting 1973
Physcia stellaris	(L.) Nyl.			N/X	0	1	1		0	1	1	0	1	0	1	Beekley & Hoffman 1981; Wetmore 1983
Physcia tenella				X	0	0	0		0	0	1	0	0	0	1	Wetmore 1983
Physconia detersa				X	0	0	0		0	0	1	1	1	1	1	Wetmore 1983
Physconia grisea	(Lam.) Poelt			N/X	0	1	0		0	0	1	0	0	0	1	Beekley & Hoffman 1981; Hawksworth & Rose 1970; Johnson 1979
Physconia pulverulenta	(schreb.) Poelt.			X	0	0	0		0	0	0	0	0	0	1	Hawksworth & Rose 1970
Ramalina calicaris				X	0	1	0		0	0	0	0	0	0	0	Hawksworth & Rose 1970
Ramalina obtusata	(Arn.) Bitt.			X	0	0	0		0	0	0	0	0	0	1	Hawksworth & Rose 1970; Wetmore 1983

Lichens	Authority	Family	Common name	SO$_2$ at < 50 ppb N = not sensitive X = sensitive	ARCH	BAND	BLCA	BRCA	CANY	CARE	GRCA	GRSA	MEVE	PEFO	ZION	References
Ramalina pollinaria				X	0	1	0		0	0	0	0	0	0	0	Hawksworth & Rose 1970
Rhizoplaca melanophthalma	(Ram.) Leuck. & Poelt.			X	1	1	0		1	1	1	0	1	1	1	Belnap & Harper 1990

Table 2-3, continued.

Lichens	Authority	Family	Common name	SO$_2$ at < 50 ppb N = not sensitive X = sensitive	ARCH	BAND	BLCA	BRCA	CANY	CARE	GRCA	GRSA	MEVE	PEFO	ZION	References
Usnea sp.				X	0	1	0		0	0	1	0	1	0	1	Vick & Bevan 1976
Usnea florida				X	0	0	0		0	0	1	0	0	0	0	Hawksworth & Rose 1970; Wetmore 1983
Usnea hirta	(L.) Weber ex Wigg.			X	0	1	0		0	0	1	0	1	0	0	Eversman 1978; Wetmore 1983; Johnson 1979
Usnea subfloridana	Stirton			X	0	1	0		0	0	1	0	1	0	1	Hawksworth & Rose 1970; Rose & Hawksworth 1981; Wetmore 1983
Xanthoria candelaria	(L.) Th. Fr.			X	0	0	0		0	0	1	0	0	1	0	Hawksworth & Rose 1970; Johnson 1979
Xanthoria elegans	(Link) Th. Fr.			N	0	1	0		0	1	1	0	1	1	1	Vick & Bevan 1976
Xanthoria fallax	(Hepp) Arn.			N/X	0	1	0		0	1	1	0	1	0	1	Beekley & Hoffman 1981; Wetmore 1983; Will-Wolf 1980
Xanthoria polycarpa	(Hoffm.) Rieber			X	0	1	0		0	1	1	0	1	0	1	Hawksworth & Rose 1970; Rope & Pearson 1990; Wetmore 1983

Grasses and Forbs

The pattern for tree experiments appears to extend to grasses and forbs. Some studies used SO_2 concentrations that greatly exceed ambient levels (200 ppb SO_2 or higher; Thompson et al. 1984) and concluded that some species were indeed sensitive to extremely high levels of SO_2 pollution. Other studies used much lower rates of fumigation. For example, Lauenroth et al. (1985) used a gradient of average SO_2 exposure from 10 to 60 ppb (with peaks as high as 100 to 800 ppb). *Agropyron smithii* was not sensitive to the lowest level of SO_2 tested, and sensitivity to higher levels depended on level of defoliation (used to simulate grazing).

Lichens and Microbiotic Crusts

As mentioned above, many people expect that lichens are sensitive indicators of SO_2 pollution. However, this universal expectation has rarely been backed up by strong proof of a direct mechanism of damage (Farmer et al. 1992). Many studies used unrealistically high concentrations of SO_2 (e.g. Nash 1973). We found many cases where lichens were determined to be sensitive to levels of SO_2 below 50 ppb (Table 2-3), but we found no cases that demonstrated sensitivity to levels as low as those that characterize the Colorado Plateau. The report that claimed the greatest sensitivity of lichens to SO_2 was one by Johnson (1979) who related the occurrence of lichen within Seattle to SO_2 concentrations. Areas with average SO_2 concentrations of just 3 ppb (and peaks of 30 ppb) had lower lichen diversity than areas with higher concentrations. However, no other covariates that may have played a role in determining lichen distribution were considered. In any case, the concentrations of SO_2 in the Colorado Plateau are substantially below even this minimum level for Seattle, so it is highly unlikely that any SO_2 impacts on lichens occur.

Weber (undated report) concluded that lichens were unlikely to be useful in monitoring air pollution in Bandelier NM because the dominant lichen forms present are crustose lichens growing on rocks (which are less sensitive to pollution than fruticose lichens growing on trees) and the occurrence of fruticose lichens is so sporadic and rare as to prevent useful observations.

Belnap et al. (submitted) examined the sensitivities of S deposition along a presumed deposition gradient around the Navaho Power Plant near Page, Arizona. They sampled lichens at distances of 6, 12, 21, 42, and 225 km from the plant. No measurements of SO_2 exposure or S deposition were included, and water-extractable sulfate of the 0-6 cm depth soil showed no pattern with distance from the plant. The rock lichens *Lecanora argopholis, Xanthoparmelia taractica,* and *Rhizoplaca*

melanophthalma showed greater chlorophyll degradation at 12 km from the plant than at other distances. Leakage of electrolytes from lichens tended to be much higher at the 6 and 12 km distances than at farther distances. No effects were apparent on rock lichens at 21 km or beyond. Conversely, cyanobacterial crusts (dominated by *Microcoleus vaginatus*) showed least chlorophyll degradation at the 12 km site; nitrogen fixing activity of *Collema tenax* (a soil lichen) was higher at 42 and 225 km than at closer distances. Unfortunately, the experiment had no replication of sites (all samples for each distance were taken from one location), so any differences in lichen condition among study sites could result from distance from the power plant or from other difference among sites unrelated to the power plant.

Most of the National Parks of the Colorado Plateau have substantial areas covered by microbiotic crusts. These crusts are assemblages of lichens, algae, moss, cyanobacteria, fungi and bacteria, which form continuous cover with relief of 1 to several cm. The crusts have been referred to as cryptogamic, cryptobiotic, microphytic, and other names. Key features of these crusts include stabilization against wind erosion by virtue of gluing soil particles together (primarily by cyanobacterial filaments; Williams et al. 1995a,b), and symbiotic N fixation. The crusts are very sensitive to trampling by animals, hikers, and vehicles (including mountain bikes), and some concerns have been raised about the potential sensitivity of the crusts to air pollution (cf. St. Clair et al. 1993). Belnap et al. (unpublished MS) examined the sensitivities of crusts and lichens to deposition in a series of experiments. They exposed crusts (from both sandstone and limestone substrates) containing *Microcoleus vaginatus* to a range of pH rainfall, from 3.5 to 6.5 (1:1 sulfuric acid:nitric acid), and found that chlorophyll content *increased* with declining pH. No evidence indicates any unusual sensitivity of microbiotic crusts to air pollution.

Sensitivity of Aquatic Ecosystems

Acidification

In discussions of surface water chemistry, we refer to the "sensitivity" of stream water to chemical change. This sensitivity can be gauged as the acid-neutralizing capacity (ANC; typically measured as 10^{-6} mol of charge/L, $= \mu mol_c/L = \mu eq/L$), or the ability of the stream water to buffer incoming acids. When acid deposition falls on stream watersheds, located on bedrock that is resistant to weathering, the result can be a decrease in the ANC and pH in the stream water.

Depending on the chemistry of the deposition and chemistry of watershed soils there may also be increases in sulfate, nitrate, and aluminum (leached by acids from soils and sediments).

The chemistry of bedrock and soils of the Colorado Plateau, along with the relatively high buffering capacity of waters, generally results in aquatic ecosystems that are unlikely to acidify due to wet and dry deposition (Turk and Spahr 1991). Surface waters of the Colorado Plateau were not included in the national assessment of the status of sensitive water bodies to acid deposition carried out under NAPAP (National Surface Water Survey, Charles 1991). The preliminary mapping of the potentially susceptible surface waters was assembled by Omernik and Powers (1982) based on the ANC of fresh waters. Fresh waters with an ANC of less than 100 μeq/l were considered potentially sensitive to acid deposition; below 50 μeq/L ANC waters were considered to be extremely sensitive. Chemical changes in surface waters can affect biological populations. The organisms most likely to respond to changes in the chemistry of surface waters include: native fish species, aquatic insects or insects with aquatic larvae, and zooplankton. The three most important water chemistry factors affecting the response of species are hydrogen ion (pH), calcium, and aluminum (Baker et al. 1990).

Phytoplankton are single-celled algae that are free-floating in lakes and ponds and provide a food source for higher organisms (e.g. zooplankton) in aquatic systems. Phytoplankton species can be affected by changes in surface-water chemistry, especially by changes in pH in the range of 5-6. In general, the abundance and species richness of phytoplankton are affected by acidity, with acidic lakes having fewer species than similarly-situated lakes with circumneutral pH (Almer et al. 1974). However, there is no general trend in phytoplankton production with changes in pH due to the fact that populations of acid-tolerant algal species increase as pH drops. Insect taxa differ greatly in their response to acidity. Mayflies (Ephemeroptera) are quite sensitive, while stoneflies (Plecoptera) and caddisflies (Trichoptera) show a greater variability in response (Baker and Christensen 1991). Amphipods, mollusks, and crustaceans also decline in lakes and streams with lowered pH.

Some evidence indicates that amphibian life history stages in eastern U.S. waters have been adversely affected by acid deposition. In the Rocky Mountain region the only experimental dose-response information for amphibian effects due to episodic acidification comes from the Harte and Hoffman (1989) study of tiger salamanders (*Ambystoma tigrinum*). In low-ANC waters on the western slope of the Rockies, salamander eggs had an lethal-dose-50 (LD-50) pH of 5.6, a value observed in these high-elevation ponds during snowmelt runoff. A more recent set of lab experiments showed that competition between larval forms of *Ambystoma tigrinum* and *Pseudacris*

trisertiata (chrous frog) (species found on the western slope of the Rockies) can be affected at pH levels of 6.0 or lower (Kiesecker, 1996).

Chronic Versus Episodic Acidification

In the early 1980s, researchers were primarily interested in the process of chronic acidification of lakes and streams caused by added sulfate from wet and dry deposition (Turner et al. 1990). This process occurs when the ANC of the streams is lost over the long-term and the pH drops as a consequence of the addition of sulfuric acid to watersheds. Deposition of sulfate to sensitive watersheds results in leaching of base cations from soils, soil acidification, and surface water acidification. This occurs as the H^+ in deposition replaces base cations on the soil exchange complex, and these nutrient cations then leach into aquatic systems in company with sulfate anions. In some watershed soils, particularly those studied in the southeastern U.S., sulfate in rain is adsorbed in soils until the soils are saturated. Then the sulfate begins to leach out into the stream waters, resulting in "delayed" acidification of streams (Church et al. 1992).

In the mid-1980s, researchers began to investigate the temporary acidification of streams due to large rain and snowmelt events, known as episodic acidification (Wigington et al. 1990, 1996). Studies focused on short-term changes in ANC, pH, and aluminum in stream water and attempted to relate the chemical changes to fish responses. These studies also began to focus attention on the role of nitrate in episodic acidification. In this situation, large rain storms lead to large increases in nitrate in stream water. This process seems to be the result of both atmospheric deposition of nitrate and loss of nitrate from the watershed vegetation and soils. Examples of episodic acidification are found in the eastern U.S. (Webb et al. 1995). In the western U.S., episodes of lowered pH and ANC have been detected under ice cover in lakes found at high elevations in the Rockies and Sierra Nevada (Turk and Spahr 1991; Stoddard 1995).

The closest region to the Colorado Plateau classified as sensitive under the NAPAP surface water assessment is the southern Rocky Mountains. As noted above, the chemistry of bedrock and soils of the Colorado Plateau, along with the relatively high buffering capacity of waters, results in aquatic ecosystems that are not likely to become acidified due to deposition in the wet or dry forms.

In parks of the Colorado Plateau the only aquatic systems that need to be evaluated for sensitivity to deposition inputs, either of acids or nutrients, are small rock pools (known as tinajas for longer lived pools connected during rain events or potholes for isolated ephemeral pools not part

of a drainage system) and headwater streams that receive most of their input water from rainfall (Graham 1991). These water bodies do support diverse communities of organisms (Dodson 1991), which could be affected by inputs of acids or nutrients. However, even in these situations the sediments found in rock pools are likely to buffer an extremely acidic rainfall event.

Nitrogen Saturation

Nitrogen saturation of watersheds is becoming more of a concern because of loadings of nitrate and ammonium in precipitation. Nitrogen saturation is defined as the state where an ecosystem can retain no additional N, and inputs match outputs (Brown et al. 1988). Some other scientists bend the definition of the word "saturation" to mean a condition when outputs rise above 0, regardless of the size of the inputs (EPA 1995). Excessive N inputs can lead to leaching of nitrate into surface waters, which in turn can affect nitrogen chemistry in surface waters, eutrophication, and, possibly, episodic and chronic acidification (Stoddard 1994).

Evidence for substantial leaching of nitrate has accumulated from a variety of sources across North America and Europe (Aber et al. 1989, Johnson and Lindberg 1992). In streams monitored in the northeastern U.S. and in the mid-Appalachian Highlands, nitrate is now observed at high concentrations during hydrologic episodes and during baseflow periods. There are a number of explanations for this nitrogen loss, including the maturation of forests (low rates of biomass accumulation in older forests may reduce the ecosystem's ability to retain N), effects of insect infestation, and excess nitrogen supply in deposition.

There is evidence that nitrogen deposition in rain, snow, and dry fall has caused small, chronic losses of ANC in high-elevation lakes in the West. The EPA's Western Lake Survey detected measurable amounts of nitrate in lakes found in northwestern Wyoming and the Colorado Rockies (especially in Front Range locations). These concentrations are high enough to indicate that some high elevation watersheds have little remaining capacity to absorb nitrogen in deposition (EPA 1995). Because there are no baseline records, these inferences depend heavily on an assumption that nitrate leaching from watersheds would not occur in the absence of elevated deposition from the atmosphere, which remains highly debatable.

The EPA Acid Deposition Standards Feasibility Study (EPA 1995) included modelling efforts focused on sensitive surface waters in the eastern United States, ecosystems that have been extensively studied and that are known to be affected by deposition of nitrogen, sulfur, and acidity. No attempt was made to model the effects of nitrogen deposition on watersheds and surface waters

of the Colorado Plateau.   Most of the terrestrial ecosystems of the Colorado Plateau are probably nitrogen-limited, but many important research questions remain. The effects of current or future rates of N deposition on plant communities remains largely unexplored, as do the potential side effects on water quality and biological populations of aquatic ecosystems on the Plateau.

Eutrophication

The addition of nutrients (primarily nitrogen and phosphorus) to surface waters can stimulate algal blooms and growth of submerged vegetation, leading to wide swings in oxygen availability in waters and losses of aquatic fauna (Laws 1993).   The eutrophication of shallow areas of Chesapeake Bay is an example of cultural eutrophication that can be traced, in part, to atmospheric deposition of nitrogen (EPA 1994). Most of the evidence to date on the effects of deposition of nitrogen on water bodies had been reported for estuarine systems, where nitrogen, rather than phosphorus, is often the limiting nutrient. Other adverse impacts of eutrophication include loss of water clarity and aesthetic qualities of freshwater bodies and odor.

Conclusions on Regional N and S Deposition

Current rates of N and S deposition on the Colorado Plateau are very low compared to other regions of the U.S. and Europe, where much of the concern about acidification, N saturation, and eutrophication developed. Most of the Class I NPS Areas of the Colorado Plateau have soils that are unlikely to be acidified easily by N or S (Binkley 1992). Most of the ecosystems are probably N limited, and may respond with increased growth if N deposition rates rise substantially. The ecosystems in the region that may be most sensitive to atmospheric deposition are probably high alpine ecosystems, where the lack of soil development or easily weathered rock may allow deposited N and S to reach aquatic ecosystems with little buffering by terrestrial ecosystems. This possibility warrants experimentation, although it is outside the Class I NPS Areas of the Colorado Plateau.

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